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# Watershed response and land energy feedbacks under climate change depend upon groundwater.

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1 Watershed response and land energy feedbacks under climate change depend upon groundwater.

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7 **Human induced climate change will have a significant impact on the hydrologic**  
8 **cycle, creating changes in fresh water resources, land cover, and feedbacks that are**  
9 **difficult to characterize, which makes it an issue of global importance. Previous studies**  
10 **have not included subsurface storage in climate change simulations and feedbacks. A**  
11 **variably-saturated groundwater flow model with integrated overland flow and land-**  
12 **surface model processes[1-3] is used to examine the interplay between coupled water and**  
13 **energy processes under climate change conditions. A case study from the Southern Great**  
14 **Plains (SGP) USA, an important agricultural region that is susceptible to drought, is used**  
15 **as the basis for three scenarios simulations using a modified atmospheric forcing dataset to**  
16 **reflect predicted effects due to human-induced climate change. These scenarios include an**  
17 **increase in the atmospheric temperature and variations in rainfall amount and are**  
18 **compared to the present-day climate case. Changes in shallow soil saturation and**  
19 **groundwater levels are quantified as well as the corresponding energy fluxes at the land**  
20 **surface. Here we show that groundwater and subsurface lateral flow processes are critical**  
21 **in understanding hydrologic response and energy feedbacks to climate change and that**  
22 **certain regions are more susceptible to changes in temperature, while others to changes in**

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**precipitation. This groundwater control is critical for understanding recharge and drought processes, possible under future climate conditions.**

The Southern Great Plains region of the USA is an important agricultural region that has experienced severe droughts over the past century including the “dust bowl” of the 1930’s [4]. This system is different than the mountain regions investigated previously[5-7] with little winter snowpack, rolling terrain and seasonal precipitation. There is evidence that while drought timing may depend upon sea surface temperature, the length and depth of major droughts in the region depend on soil moisture conditions and land-atmosphere interactions [4, 8-10].

There is a growing body of work on mountain hydrology and snowpack response to changing climate, particularly in Western North America [e.g. 5, 6, 7]. Recent work has begun to investigate the impact of climate change on groundwater recharge and storage [11-15]. These studies have shown changes in groundwater recharge in response to climate change[12-15] and the role of groundwater in maintaining baseflow under an altered climate[11]. However, these studies have not included feedbacks from groundwater to the land surface, particularly the land surface energy budget recently shown to be an important feedback [2, 16].

Here, we study the response of a watershed in the Southern Great Plains (SGP) in Oklahoma, USA using a unique, integrated groundwater-surface water-land surface model. Perturbed forcing input is developed to represent plausible climate change scenarios and used to drive the coupled model. Results include both the watershed response, such as changes in soil moisture, recharge and water table depth, and land surface feedbacks including changes in the energy budget. Three future climate scenario simulations were generated by perturbing the control run (CNTRL) with the atmospheric conditions of the water-year 1999. All perturbations consisted of a systematic increase in air temperature by 2.5K with 1) no precipitation change (H:

hot); 2) an increase in precipitation by 20% (HW: hot and wet); and 3) a decrease in precipitation by 20% (HD: hot and dry). These perturbations were meant to represent the variability and uncertainty in regional changes to Central North America under global simulations of future climate[17].

Figure 1 plots yearly-averaged 1) saturation, 2) water table depth, 3) recharge, 4) ground surface temperature and 5) latent heat flux for CNTRL and the difference for each scenario minus CNTRL. This figure shows that, in general, the saturation decreases slightly for H (b1), increases for HW (c1) and decreases significantly for HD (d1). Closer inspection reveals that the soil moisture does not change in the river valleys, even for the dry scenario HD (d1). This is due to lateral subsurface redistribution of water, which converges in the valleys, maintaining soil moisture at higher values. These patterns of surface-subsurface interplay are reinforced by viewing the water table depth and differences (Figure 1, a2-d2). Panel a2 clearly shows the river valleys as the dark blue regions with values of water table depth less than two meters. These panels show no difference in water table depth between the scenarios and CNTRL in the river valleys, however there is an increase in water table depth especially along the hillslopes in scenarios H (b2) and HD (d2) and an increase in water table depth in HW (c2).

The plots of recharge, precipitation minus total evaporation and transpiration (P-E), in Figure 1, a3-d3 demonstrate significant spatial variability in all cases. This figure indicates that recharge is negative in the river valleys in all cases, while recharge elsewhere is positive in the CNTRL (a3), negative in H (b3), positive in HW (c3) and strongly negative in HD (c4).

In Figure 1, plots of ground temperature (a4-d4) are also spatially heterogeneous due to convergent flow and spatially distributed vegetation and soil cover. This figure shows that for scenario H (b4) yearly-averaged increases in ground surface temperature are greater than the

increases seen from scenario HW (c4) but not as great as HD (d4). Scenario HD shows a clear influence of convergent groundwater flow in the river valleys with smaller temperature increases corresponding spatially to locations with small groundwater and saturation differences. Panels a5-d5 also show that latent heat fluxes vary spatially with larger values in the river valleys than the hilltops. All scenarios show additional increases in latent heat flux in the river valleys (b5-d5). Outside the river valleys scenario H (a5) shows slight increases in latent heat fluxes, HW (b5) shows strong increases (b5) and HD (d5) shows moderate to strong decreases.

Careful inspection of Figure 1 reveals that much of the variability in recharge and energy fluxes appears to be spatially correlated with groundwater depth. Figure 2 explores this spatial variability further, plotting yearly-averaged latent heat flux (a), latent heat flux difference (b), recharge (c), and recharge anomaly (d) as a function of water table depth for all cases. In this figure it is shown that in the river valleys, where groundwater is shallow, latent heat fluxes are largest (a) and recharge is negative (c), due to a constant supply of water to the land surface. Conversely, where groundwater is deep we see the smallest values of latent heat flux (a) and recharge (b) due to water limitations at the land surface. Figure 2a and 3c also show that for groundwater depths between two and five meters there is a strong correlation between recharge and latent heat flux and water table depth. These relationships have been explored previously [2] and this region is the so-called critical zone where subsurface and land surface processes are most tightly coupled.

Figure 2b also shows a significant impact of groundwater on latent heat flux differences between the scenarios and the control. This Figure shows very little difference between scenarios for shallow water table depths and the largest differences at great water table depth. In the river valley, all scenarios show an increase in latent heat flux at small water table depths due

to the uniform increase in temperature. At large water table depths (at the hill tops) we see large differences in latent heat flux due to differences in precipitation. This is reinforced by HW having a large positive difference in latent heat flux, HD a large negative difference and H (with the same rainfall as CNTRL) almost no difference at all. In the critical zone, where groundwater depths range from two to five meters, we again see a strong correlation between water table depth and difference in latent heat flux indicating the control groundwater exerts on the watershed response as a consequence of the climate change scenarios. We also see in this Figure that the influence of vegetation type on latent heat flux is small compared to groundwater.

Figure 2d shows that the P-E anomaly (difference in recharge between each scenario and CNTRL) depends on water table depth as well. At shallow depths the P-E anomaly is due to differences in precipitation as evapotranspiration is very similar in all scenarios, shown in Figure 2a. For a deeper water table there is less variability in the P-E anomaly between scenarios and more scatter in the curves. This scatter is due to differences in land cover and soil type and the P-E anomaly is due to a combination of the differences in parameters for these soil and vegetation types and rainfall amount. Again we see a strong dependence of the P-E anomaly on groundwater depth in the critical zone between two and five meters. At large water table depths groundwater is disconnected from the land surface and the land surface is in dynamic equilibrium with atmospheric forcing. These equilibrium conditions would be expected over the entire model domain from traditional land surface models that lack lateral subsurface flow. This is particularly important because the spatial variability in water table depth significantly affects the spatial average in the P-E anomaly, shown by the colored horizontal lines for each case. These average P-E anomalies show strong drought conditions for H (-0.1mm/d), comparable to the “dust bowl” of the 1930’s and the drought in the 1950’s [18]. HW demonstrates an increase

in P-E anomaly and HD shows a significant decrease in P-E anomaly (-0.2mm/d) twice the value of any drought on record in the region over the last century. Figure 2d clearly shows that the severity of the basin-averaged drought conditions would be significantly underestimated by land surface processes alone, without the inclusion of lateral groundwater flow.

In Figure 2a and b, the large annual changes in latent heat flux also indicate the potential for land-atmosphere feedbacks for scenarios H and HD. Both cases show an increase in latent heat flux in the river valley and either no change or a significant decrease in latent heat flux at the hill tops. Previous work has documented the potential for land-atmosphere feedbacks [e.g. 16, 19, 20] and the current simulations indicate that these feedbacks would be amplified. The strong convective conditions created by large spatial energy flux gradients could indeed feedback to maintain dry conditions [e.g. 21].

In summary, this study uses an integrated watershed model with coupled hydrology and land surface energy components to investigate watershed response, interactions and feedbacks from future climate scenario simulations. It is shown that groundwater storage acts as a moderator of watershed response and climate feedbacks. In zones with a shallow water table, the changes in land surface energy fluxes are primarily a function of atmospheric temperature increase as these processes are never water limited. In areas where the water table is deep, changes in land surface energy fluxes are mostly a function of precipitation because there is little feedback from groundwater. In the so-called critical zone [2], between two and five meters in this study, very strong correlations between water table depth and land surface energy response are demonstrated. These findings also have strong implications for drought as P-E anomalies also demonstrate a strong dependence on areas of convergent flow and water table depth. These findings suggest that the energy feedbacks from the land surface could impart a significant signal

in the lower atmosphere, which might in turn modify atmospheric response. Although the area studied is regional in size, the results suggest that the role of lateral subsurface flow should not be ignored in climate change simulations and drought analysis.

#### *Methods*

The model ParFlow was used in this study. It is a fully integrated, parallel watershed model [1-3, 16, 22, 23] and is capable of simulating fluid, mass, and energy transport processes in the deep subsurface, the vadose zone, root zone and land surface. This includes integrated overland flow (river and hillslope flow [1]) and a land surface model, CLM, [2, 3, 24] which accounts for energy and plant processes at the land surface.

ParFlow was applied to the Little Washita watershed in Oklahoma, USA with a model domain was 45km x 32km. The simulations used a 1km lateral and 0.5m vertical discretization with a very deep subsurface to fully capture both shallow subsurface and deeper groundwater lateral flow[2]. The spatially heterogeneous soil of the watershed is mostly loamy sand, sand, with some sand and silt loam. The watershed is rolling terrain covered by grass with shrubs and interspersed trees. The elevation, soil and vegetation cover data for this domain have been previously published [2, 16].

Four equilibrium simulations were conducted: one control based upon current and three perturbations based upon future global climate model predictions [17 Table 11.1]. The simulation of the current climate scenario (CNTRL) based upon water year 1999 is documented in [2]. In CNTRL, spatially uniform atmospheric forcing derived from North American Regional Reanalysis (NARR) for water-year 1999 was interpolated to one hour intervals to create a continuous time series of precipitation, air temperature, downward solar radiation, air pressure, wind and relative humidity.

The three future climate scenario simulations were generated by perturbing the water-year 1999 time series. The perturbations consisted of 1) a systematic increase in air temperature by 2.5K with all other forcing variables unchanged (H); 2) an increase in air temperature by 2.5K with an increase in precipitation by 20% (HW); and 3) an increase in temperature by 2.5K with a decrease in precipitation by 20% (HD). Each of the scenarios was spun-up, that is, started from the CNTRL state and forced repeatedly with the perturbed dataset until changes in the mass and energy balance over the year dropped below a threshold. All simulations were performed on the LLNL parallel computer, *Thunder*, a 4,096 processor 64-bit parallel computer. 20 cpus were used per simulation case and a spinup time of three years was required.

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#### *Figure Captions*

Figure 1. Plot of yearly-averaged saturation (1), water table depth (2), recharge (3), ground surface temperature (4) and latent heat flux (5) for the CNTRL (a) and differences between H (b), HW (c) and HD (d) and CNTRL for each of the variables. Note the watershed outline plotted on each panel. Note individual panels are referred to as a number-letter grid (e.g. a1) for CNTRL-Saturation.

Figure 2. Semi-logarithmic plot of yearly-averaged latent heat flux (a) and latent heat flux difference (b) as a function of the water table depth of CNTRL for each of the scenario cases as indicated and semi-logarithmic plots of recharge (c) and P-E anomaly (d) as a function of water table depth for two vegetation types as indicated in plot b. Spatial averages of P-E anomaly are

185 shown for each scenario by the dashed lines of corresponding color to the symbols. Note also in  
186 this figure that ET=evapotranspiration, P=precipitation, LS=land surface processes and  
187 GW=groundwater.

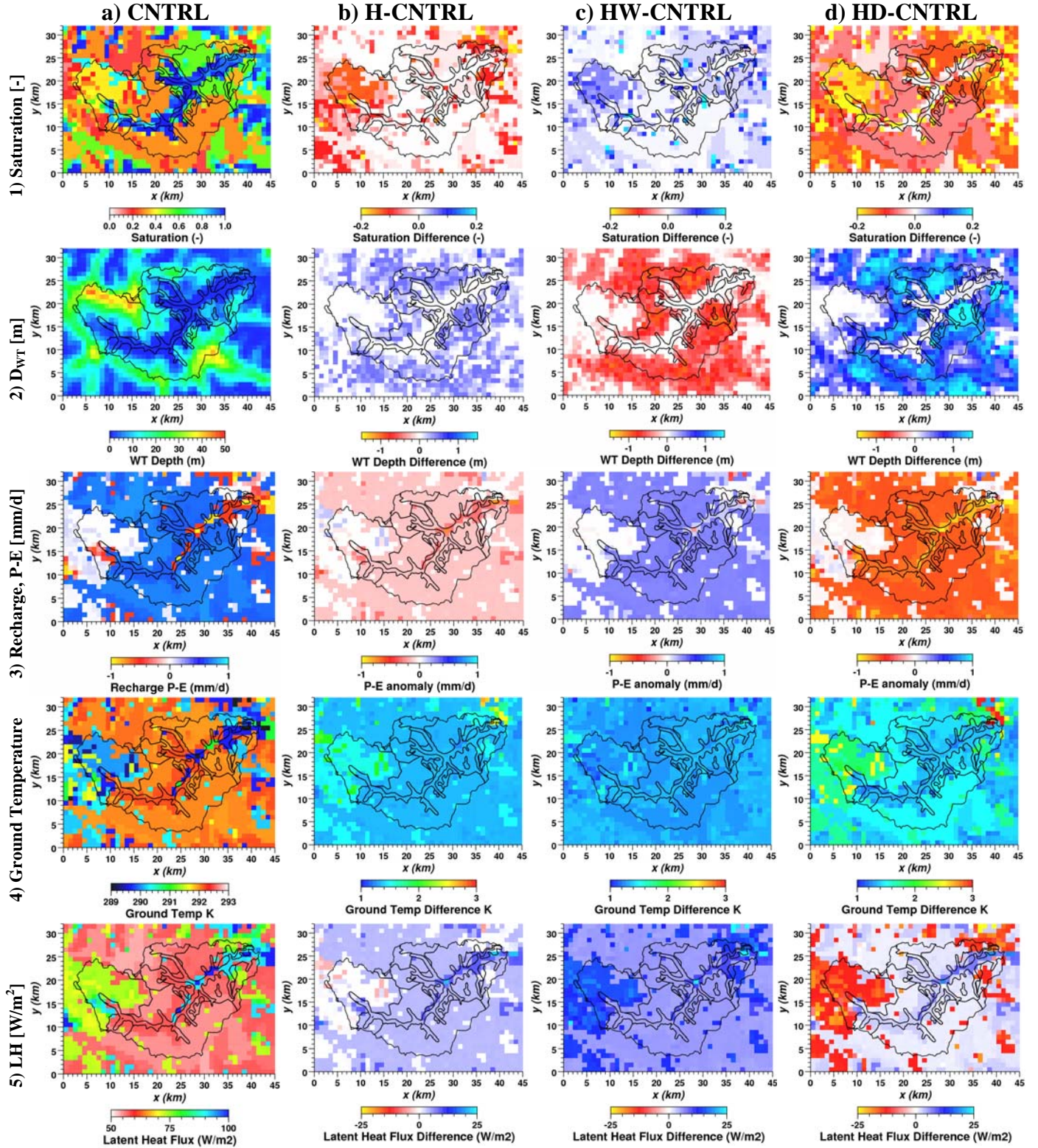


Figure 1. Plot of yearly-averaged saturation (1), water table depth (2), recharge (3), ground surface temperature (4) and latent heat flux (5) for the CNTRL (a) and differences between H (b), HW (c) and HD (d) and CNTRL for each of the variables. Note the watershed outline plotted on each panel. Note individual panels are referred to as a number-letter grid (e.g. a1) for CNTRL-Saturation.

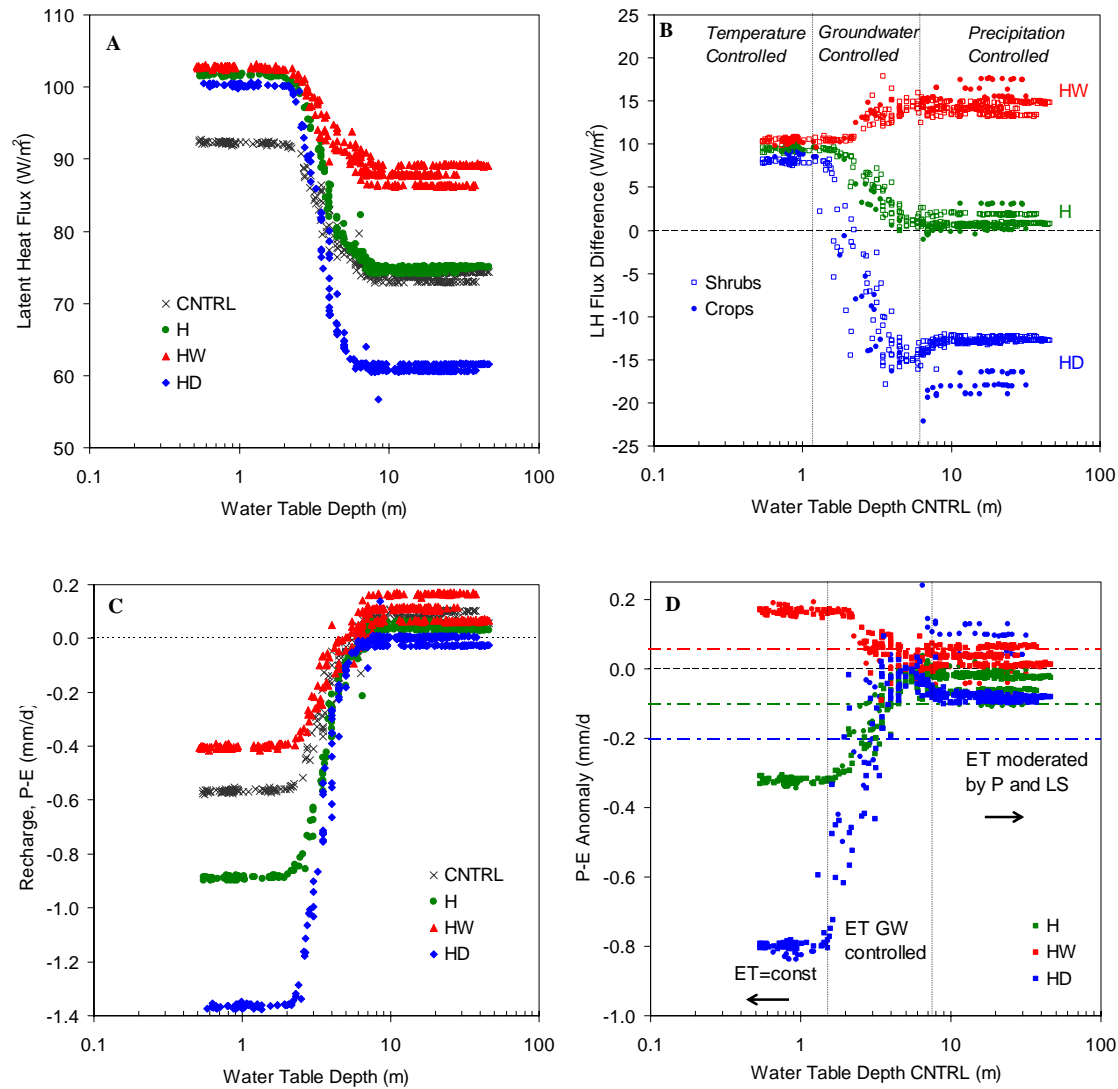


Figure 2. Semi-logarithmic plot of yearly-averaged latent heat flux (a) and latent heat flux difference (b) as a function of the water table depth of CNTRL for each of the scenario cases as indicated and semi-logarithmic plots of recharge (c) and P-E anomaly (d) as a function of water table depth for two vegetation types as indicated in plot b. Spatial averages of P-E anomaly are shown for each scenario by the dashed lines of corresponding color to the symbols. Note also in this figure that ET=evapotranspiration, P=precipitation, LS=land surface processes and GW=groundwater.

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